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Soil Ecosystem Changes During the Transition to No-Till Cropping

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Soil Ecosystem Changes During the Transition to No-Till Cropping

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SUMMARY. Growers in the United States and worldwide are adopting no-tillage (no-till) cropping to reduce soil erosion, improve soil quality, increase water infiltration, and reduce number of passes with farm equipment over their fields. Soil erosion from dry farmed (i.e., non-irrigated) cropland in most regions of the United States exceeds the tolerable rate. An understanding of the changes in the soil ecosystem with changing tillage practices is needed to minimize the impact of agriculture on the environment and foster the use of sustainable agricultural practices. The soil biota is critical to the functioning of any agroecosystem, but studying the soil biota is difficult due to the diversity and the challenges associated with isolating and identifying these organisms. Soil disturbance or lack of disturbance can have a profound effect on biotic populations, processes and community structure. This contribution examines changes that occur in soil during the transition to no-till crop-

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ping, interrelations among organisms in the soil food web, and the relationships between organisms and their environment. As interest grows in sustainable cropping systems that mimic processes and soil organic matter turnover of native, undisturbed systems, it is imperative to understand how the transition to no-till affects an organism's niche, or functional role within the soil environment. Ecosystem investigations will enhance the understanding of changes that occur with the adoption of reduced tillage and no-till cropping systems so that these systems become increasingly viable. *[Article copies available for a fee from The Haworth Document Delivery Service: 1-800-HAWORTH. E-mail address: <docdelivery@haworthpress.com> Website: <http://www.HaworthPress.com> © 2004 by The Haworth Press, Inc. All rights reserved.]*

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KEYWORDS. No-till, conventional tillage, conservation tillage, microorganisms, fauna, residue management

INTRODUCTION

Degradation of agricultural soils caused by excessive tillage has spurred interest in minimum tillage and no-till cropping practices. No-till cropping creates the physical conditions of surface-managed residues and undisturbed soil that leave soil less susceptible to wind and water erosion (Baker, Saxton, and Ritchie, 1996). Maintenance of surface residues often increases microbial populations and diversity. Soil organic matter (OM) levels increase with no-till and soil may sequester C that would otherwise be released to the atmosphere as CO_2. In spite of the advantages of no-till farming, making the transition to no-till from tillage-based cropping is not without challenges. Research to determine soil biotic and agronomic changes, and economic feasibility during the transition from conventional tillage to no-till is ongoing. The study of soil biota is difficult due to the vast number and diversity of organisms, and the problems associated with isolating and identifying the soil's biotic community (Hawksworth and Mound, 1991).

With less soil disturbance, changes in soil nutrient status and the plant/microorganism interaction within the soil environment occur that may change the type and number of organisms present. As interest grows in developing sustainable cropping systems that mimic the processes and soil OM turnover of native, undisturbed systems, it is imperative to understand how the shift to no-till practices affects an organism's niche, or functional role within the soil environment.

TILLAGE PRACTICES

We define no-till cropping as planting directly into the residue of the previous crop without any tillage operations that mix or stir the soil prior to planting. No-till, also known as direct seeding, opens the door in all production zones for energy savings, improved soil quality, and excellent control of wind and water erosion. Adoption of minimum tillage and a continued movement toward no-till is needed to reduce soil erosion to tolerable levels. Acceptance of no-till is often slowed by concerns about transition costs, lack of experience and expert knowledge of no-till practices, grower resistance to change, uncertainties with crop yields, and risks of crop loss resulting from unpredictable agronomic factors. However, resource conservation and environmental benefits are favored by no-till and provide incentives for a gradual, continuing shift to this technology that is currently viewed as the farming practice of the future (Papendick and Parr, 1997). Surface residue from the previous crop is preferably left in the field, but may be swept into windrows, or removed by baling or burning in high residue situations. With conventional tillage there are many different management techniques and implements that produce differing degrees of disturbance. Moldboard plowing involves the greatest soil disturbance where the soil is inverted and about 90% of the residue buried. Minimum or reduced tillage involves some type of tillage implement (disk, chisel, cultivator, power harrow), but maintains 30% or more residue cover. In ridge tillage, ridges are made from tilled soil, and crops are planted into the ridges. With no-till there are varying levels of disturbance depending upon the type of no-till drill used. In other words, there are many gradations within no-till systems, but all cause considerably less soil disturbance compared to conventional tillage systems.

As growers reduce tillage, they may experience reduced crop yield due to interference from residue, which may reduce stand establishment due to lack of suitable no-till drills (Baker, Saxton, and Ritchie, 1996; Rasmussen, Rickman, and Klepper, 1997), increased incidence of disease (Cook and Haglund, 1991), nutrient immobilization (Elliott and Papendick, 1986), and more weeds (Kettler et al., 2000). The economics of no-till compared to tillage-based systems are often mixed, even within the same geographic region. For example, in eastern Washington State, the relative economics of no-till in the high (more than 450 mm annually) precipitation zone are generally positive (Camara, Young, and Hinman, 1999), whereas no-till cropping systems in the low (less

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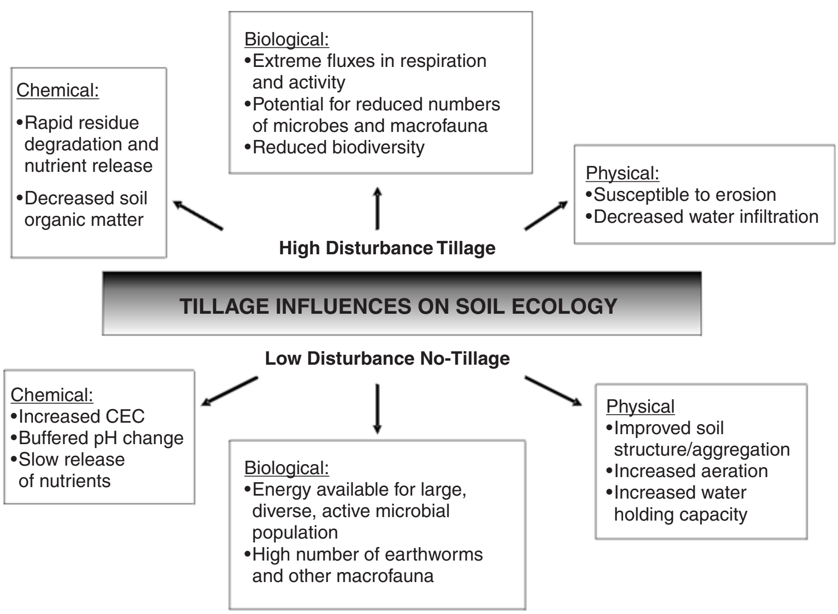
than 300 mm annually) precipitation zone are not yet as profitable as conventional practices (Young, Hinman, and Schillinger, 2001).

Crop species diversity, cropping intensity, and crop rotation may change with tillage system, and in turn affect microbial diversity (di Castri and Younes, 1990; Hawksworth and Mound, 1991; Thomas and Kevan, 1993). Tillage changes soil physical characteristics and residue decomposition as well as soil chemical and structural characteristics. These factors both directly or indirectly impact the soil biology and the soil biotic community (Figure 1). Soil microbial populations are not static or homogeneous (Mikola and Setala, 1998), but rather highly sensitive to disturbance (Elliott and Lynch, 1994), and the soil biota may be the first group of organisms to shift with changes in tillage management. Soil organisms may be used as early indicators of changes in soil quality due to tillage and other perturbations (Kennedy and Papendick, 1995). Changes in soil parameters, especially microbial factors, during the transition from conventional tillage, to minimum tillage, and ultimately to no-till vary with soil type, implement used, cropping system, precipitation, or other variables (Kennedy and Smith, 1995; Lupwayi, Rice, and Clayton, 1998).

FIGURE 1. The relationships between tillage and soil ecology.



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THE TRANSITION PERIOD

The study of soil microbial ecology is critical for our overall understanding of tillage management impacts. We refer to the changes occurring in soil physical, chemical and biological characteristics with increasing time under no-till, before reaching a new equilibrium, as the "transition period." Changes during the transition from conventional tillage to no-till may occur almost immediately or may require many years before differences can be detected (Figure 2). Effective management during the transition period is critical for the initial success of no-till systems and often dictates whether a grower continues to use no-till for the long term. Understanding the changing ecological relationships in the soil during the transition period is key to effective management. Change in soil quality with no-till compared to conventional tillage occurs most rapidly (during 1-4 years) in the surface soil (0-5 cm), and includes increased mineralized carbon (C), active microbial biomass (Alvarez and Alvarez, 2000), soil OM, aggregate stability, exchangeable Ca and extractable P, Mn, and Zn, and less extractable K, Fe, and Cu (Rhoton,

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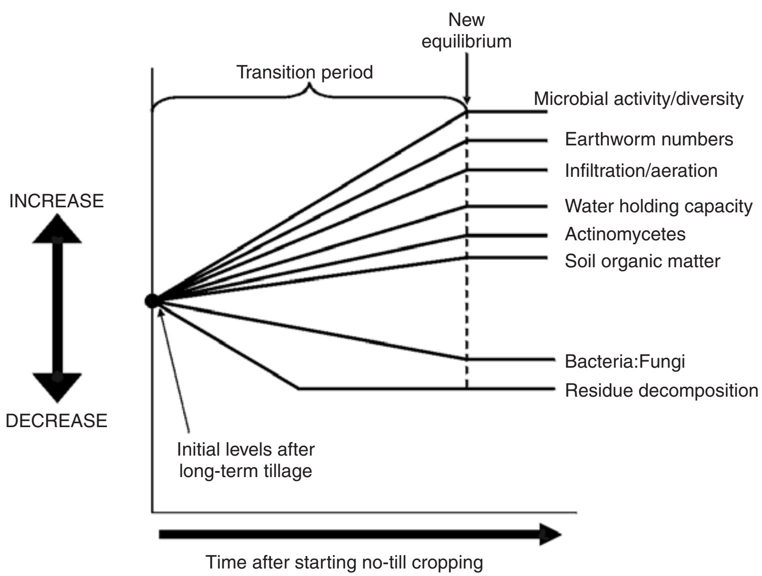
FIGURE 2. Changes in soil quality characteristics with time during the transition from tillage to no-till.



2000). After three years of no-till farming on land that was previously conventionally tilled in a cereal-fallow system in Washington State, increased electrical conductivity and readily mineralized C levels, and decreased pH were observed at two sites. Shifts in the fatty acid methyl ester (FAME) profile were associated with crop type and tillage (Stubbs et al., unpublished data). Long-term changes with no-till vs. conventional tillage include more total microbial biomass, higher contribution of microbial biomass C to organic C, and greater fungal hyphal length (Ananyeva et al., 1999). Soil quality changes are evident during the transition to no-till, but their significance in predicting the duration of this transition period or the positive or negative impacts of no-till is not yet known. The flux in soil parameters evident during this transition period will vary with soil type, climate and cropping system, thus long-term cropping system studies in numerous agro-environments are needed.

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CROP SELECTION, ROTATIONS, AND RESIDUE

Crop species, rotation sequence, and degree of cropping intensity can directly or indirectly affect the soil biotic community. Plants and their exudates influence the soil microorganisms and soil microbial community that are found near roots (Duineveld et al., 1998; Ibekwe and Kennedy, 1998; Ohtonen et al., 1999). Soil microorganisms may affect plant growth and influence plant competition among species (Westover, Kennedy, and Kelley, 1997). In turn, plants may be a selective force for rhizosphere microbial populations through their influences on exudation patterns (Meharg and Killham, 1995) and soil nutrients (Droge, Puhler, and Selbitschka, 1999; Jensen and Nybroe, 1999; Pennanen et al., 1999). The composition of the plant community may drive the composition of the soil microbial community (Achouak et al., 2000; Fulthorpe, Rhoades, and Tiedje, 1998; Minamisawa, Nakatsuka, and Isawa, 1999); microbial diversity is more responsive to differences in soil characteristics rather than plant type (Degens et al., 2000; Gross, Pregitzer, and Burton, 1995; Wardle et al., 1999).

The transition to no-till often necessitates changes in crop rotation for residue and disease management, or to manage economic risk. Increased cropping intensity and planting specific crop species, combined with reduced tillage, have been shown to improve soil quality characteristics. Drijber et al. (2000) found that Nebraska soils planted to winter wheat (*Triticum aestivum* L.) had greater microbial biomass than fallow soil, regardless of tillage intensity and that during the fallow portion of a wheat-fallow rotation, no-till fields had greater microbial biomass than fields that had been moldboard plowed. The microbial diversity of soils under wheat preceded by a legume crop [red clover (*Trifolium pratense* L.) or peas (*Pisum sativum* L.)] was higher than in wheat preceded by summer fallow or continuous wheat (Lupwayi, Rice, and Clayton, 1998). In a study in Brazil where fields had not received inoculant of the nitrogen (N)-fixing bacterium *Bradyrhizobium* for more than 15 years, no-till combined with crop rotations containing soybeans (*Glycine max* L.) resulted in higher populations and greater diversity and activity of *Bradyrhizobium* than cropping systems without soybeans (Ferreira et al., 2000).

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No-till and conventional tillage systems have vastly different quantities and types of surface residue distribution. Surface residue retention improves soil quality characteristics (Dalal, Henderson, and Glasby, 1991; Doran, Sarrantonio, and Liebig, 1996; Karlen et al., 1994; Ladd et al., 1994) by increasing OM accumulation (Nyakatawa, Reddy, and Sistani, 2001). Other benefits of surface residues include greater fungal biomass (Holland and Coleman, 1987; Karlen et al., 1994), soil C levels (Holland and Coleman, 1987; Karlen et al., 1994), earthworm populations, and microbial activity (Karlen et al., 1994). Soil aggregates are more water-stable when residue levels are doubled than when the residue is maintained or removed in continuously cropped corn in Wisconsin (Karlen et al., 1994). In a double-cropped wheat and soybean system, non-burned, no-till soil had greater numbers of algae, actinomycetes and fungi initially (Harris et al., 1995). Although increases in microbial numbers and activities may be beneficial, this may not always be the case (Kennedy and Smith, 1995). It may be more constructive to study the changes, either plus or minus, in populations or activities as indicators of flux within the ecosystem.

PHYSICAL AND CHEMICAL SOIL CHARACTERISTICS

Tillage will fundamentally change the physical and chemical characteristics of the soil and profoundly alter the matrix supporting the growth, functioning and survival of the soil biota (Table 1). Physical parameters of soil altered by tillage have a great influence on the soil ecology. Disturbance of the soil system, intact versus homogenized soil, infiltration, and residue placement are some of the changes that will affect soil organisms. Compaction of soils under long-term no-till management is a physical change that concerns growers, and greater surface

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TABLE 1. Physical and chemical attributes of changing tillage systems in select studies.

SOIL ATTRIBUTE [§]	***LENGTH OF STUDY/ YEARS OF SAMPLING***	***SYSTEMS COMPARED****	***RESULTS***	***LOCATION***	***REFERENCE***
AS, SOM, pH	0, 4, 8 yr/0, 4, 8 yr	NT, CT, cotton, sorghum-corn, and soybean-wheat rotations.	After 4 yrs NT 0-2.5 cm ↑ AS, SOM, pH unchanged.	Mississippi	Rhoton, 2000
AS, SOM	8 yr/1 yr	MP (20-25 cm) and cultivation to 12 cm.	Shallow tillage ↑ AS and SOM.	Sweden	Stenberg, Stenberg and Rydberg, 2000
SOM, pH	3 yr/3 yr	NT, CT cotton with poultry litter and winter rye cover crop.	Reduced till or NT ↑ surface SOM; winter rye cover crop and poultry litter, pH unchanged.	Alabama	Nyakatawa, Reddy and Sistani 2001
SOM	7 yr/1 yr	NT and stubble mulch tillage, winter wheat-sorghum-fallow.	NT ↑ SOM.	Texas	Unger, 1991
Distribution of C with aggregate size classes	26 (NE), 33 (OH), 9 (MI), 16 (KY)/1 yr	Native vegetation, NT, CT.	Macro- and micro-aggregate C: Native vegetation > NT > CT.	Nebraska, Ohio, Michigan, Kentucky	Six et al., 2000
pH, POM C, TOC	8 yr/2 yr	NT, chisel plow, MP	NT 0-5 cm ↑ pH; NT had greatest amount of TOC as POM, NT had greatest amount of TOC.	Illinois	Hussain, Olson and Ebelhar, 1999
TOC, pH, EC	NT 20+ yr; tillage treatments 5 yr/1 yr	NT plowed 5 yr previously, NT undisturbed, and CT	NT plow ↓ TOC 20%; NT plow ↑ pH; EC NT plow = NT undisturbed.	Nebraska	Kettler et al., 2000
TOC, microbial biomass N, pH	20 yr/1 yr	CT and NT with residue or burned	NT surface 0-2.5 cm ↑ TOC and microbial biomass N; NT with residue and urea ↓ pH.	Australia	Dalal, Henderson and Glasby, 1991
BD	3 yr/0, 3yr	NT and disk, soybean-corn rotation.	No significant changes in BD for NT soils, disking ↑ BD in 67% of cases.	Iowa	Logsdon and Cambardella, 2000
BD, water infiltration	NT 20+ yr; Tillage 5 yr/1 yr	NT plowed 5 yr previously, NT undisturbed, and CT.	NT ↑ BD; water infiltration for the second 2.5 cm of water applied was greater for NT undisturbed than NT plow or CT.	Nebraska	Kettler et al., 2000
Gravimetric moisture, pH, total C	Cultivated land cropped since 1950, forest cleared and mowed annually since 1960, sampled for 1 yr	Cultivated, annually cropped, forest that was cleared, not plowed or cropped	Cultivated ↓ C by half, ↑ moisture and pH.	Michigan	Robertson, Crum and Ellis, 1993
Denitrification and nitrification potential, inorganic N, pH	100+ yr/1 yr	Undisturbed prairie, CT wheat-barley-pea rotation.	Prairie soils ↑ denitrification and nitrification potential; cultivated ↑ inorganic N; = pH.	Washington	Kennedy and Smith, 1995

§ AS = aggregate stability, SOM = soil organic matter, BD = bulk density, POM = particulate organic matter, TOC = total organic carbon, EC = electrical conductivity.
* NT = no-till, CT = conventional tillage, MP = moldboard plow.

bulk density measurements have been found in many no-till soils (Pierce, Fortin, and Staton, 1994). However, these fears may be unfounded for some soil types. The loss of OM associated with intensively tilled, eroded soils may lead to increased bulk density (Edwards 1991; Karlen et al., 1990). Logsdon and Cambardella (2000) showed that in several fine-loam soils, soil bulk density remained constant for the first three years of no-till management. In three of four rice producing study sites in Bangladesh, use of no-till with mulch, compost and green manure resulted in lower bulk density than systems using conventional tillage and inorganic fertilizers (White et al., 2001). Changes in bulk density with during the transition to no-till will most likely vary by location, and are dependent on such variables as soil type, OM content, cropping system and climate (Kettler et al., 2000). Detrimental increases in soil bulk density can often be avoided in no-till regimes by operating equipment under proper soil moisture conditions.

Beneficial soil quality changes are often observed between long-term deep cultivation, and shallow tillage practices. Stenberg, Stenberg, and Rydberg (2000) showed that in fields cultivated to a depth of 12 cm, soil OM and microbial biomass increased and led to improved aggregate stability compared to conventional moldboard plowing at 20-25 cm depth. Greater aggregate stability is most likely the result of increased OM supporting greater microbial biomass that exuded extracellular metabolites such as polysaccharides and proteins to cement soil particles into larger, more stable aggregates (Stenberg, Stenberg, and Rydberg, 2000).

Worm and root channels may enhance water infiltration and reduce runoff (Edwards et al., 1992). In the steeply sloping Palouse region of southeastern Washington and northern Idaho, soil loss by water erosion during a single winter season may exceed 50 Mg ha^{-1}. The worst erosion typically results when snowmelt and/or rain occurs on thawed soil overlying a subsurface frozen layer (McCool, 1990). No-till growers in this region credit worm channels, that extend from the soil surface to depth, for improved soil water infiltration and reduced erosion in their fields (John Aeschliman, personal communication). Intact channels from reduced soil disturbance and lack of soil mixing each season result in less mixture of substrates for microbial growth. Tillage may lead to soils with a greater proportion of microaggregates, which are C-depleted, compared to macroaggregates, which contain more C than microaggregates (Six et al., 2000).

Despite all of the advantages of reduced tillage, physical soil disturbance is beneficial in some agricultural systems. Abawi and Widmer

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(2000) cite numerous examples where yield of beans due to disease was reduced when the soil was subjected to reduced tillage or no-till compared to intensive tillage. The increase in yield with tillage was attributed to reduced compaction, improved drainage, and higher soil temperature that led to improved bean root competition against pathogens. In several wheat production regions of the world, Rhizoctonia root rot caused by *Rhizoctonia solani* (Kühn) AG8, is an important disease of crops planted into cereal stubble with no-till (Weller et al., 1986). Rhizoctonia is a minor disease of cereals grown under conventional tillage, but can be devastating for these crops in no-till cropping systems. The most effective practices that limit the severity of this disease in no-till cropping systems are (i) elimination of volunteer and other grass weeds that serve as hosts for the pathogen during the "green bridge" period of 2-3 weeks and preferably 2-3 months prior to planting wheat (Smiley et al., 1992), and (ii) soil disturbance in the seed row 5-6 cm below the seed at the time of planting (Roget et al., 1996). There are presently no wheat cultivars that are resistant to *Rhizoctonia*.

Some soil chemical changes that vary with tillage exert a subtle effect on soil organisms. Long-term depletion and homogenization of nutrients may affect the soil community, but it is difficult to measure these changes when nutrient content is altered by the distribution of the substrate and OM. Organic matter and N concentrations are more uniform throughout the soil zone mixed by tillage than under no-till (Unger, 1991). Organic matter content is greater in surface soils of no-till systems compared to tilled systems; however, the increase in OM with reduced tillage is not always evident at lower soil depths (Unger, 1991). It is possible that the differences between cultivated and undisturbed lands are due to C and N depletion (Cavigelli and Robertson, 2000; Paul et al., 1999). With long-term cultivation, C and N pools are homogenized and C pools have been depleted by 89% and 75%, respectively (Knops and Tilman, 2000). In intensively tilled cropping systems, the exhausted C and N pools are not readily re-established even with conservation practices (Drinkwater, Wagoner, and Sarrantonio, 1998; Knops and Tilman, 2000). As would be expected, the homogenization of nutrients is greatest with increased tillage intensity (Robertson, Crum, and Ellis, 1993). Bacterial populations tend to decline under low pH, whereas low pH has less effect on fungal communities. Soils with similar C and N levels may have similar microbial community composition (Wardle et al., 1999; Zak et al., 2000).

Stubbs (2000) showed that residue quality, and decomposition of wheat straw in soil varied widely among cultivars and that decomposition is correlated with acid detergent fiber, lignin, total N and C:N ratio. Knowledge of differences in wheat cultivar decomposition rates is important for growers in both high and low precipitation regions where excessive straw production may interfere with planting operations or, conversely, where straw may not be in sufficient quantity to control erosion.

Response of soil enzymes to tillage is site-specific, and more dependent on soil characteristics and sampling protocol than management (Bergstrom, Monreal, and King, 1998). Two sites in Ontario were assayed for the soil enzymes dehydrogenase, urease, glutaminase, phosphatase, arylsulfatase, and β-glucosidase. At the site with no-till and prior history of forages including alfalfa (*Medicago sativa* L.) in the crop rotation, there were increases in all of the soil enzymes assayed. At a separate site, differences in enzyme concentration were not consistent with management, and depended more upon soil texture and sampling depth than differences in tillage (Bergstrom, Monreal, and King, 1998).

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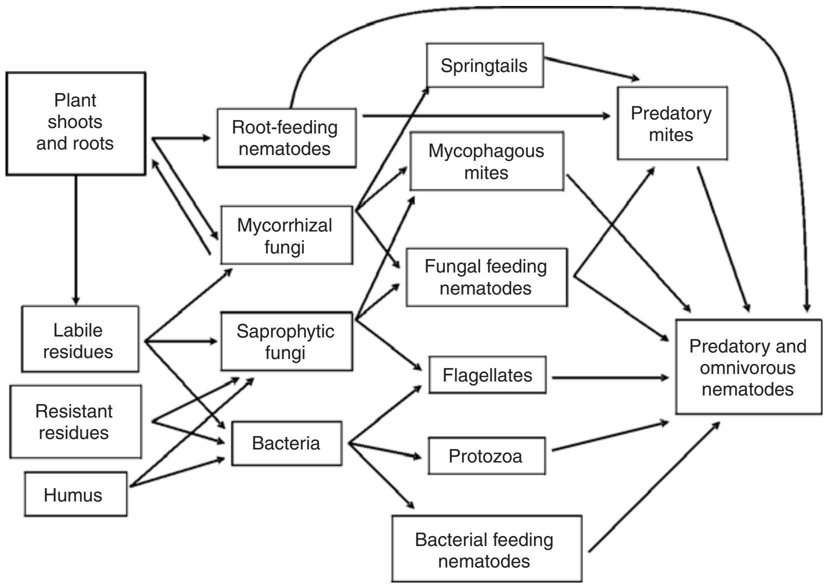
SPECIFIC GROUPS OF ORGANISMS

The organisms of the biotic community in soil can be viewed as an interconnected web, where each portion of the web interacts with other members of the soil community (Figure 3). A soil food web contains different trophic levels ranging from bacteria and fungi to carnivorous animals. The members of the soil food web have a profound effect on crop production through processes such as residue decomposition and nutrient cycling. Plants, with their spreading root systems, are able to access a large volume of soil and supply soil organisms with nutrients. This is especially true in the vicinity of the rhizosphere, where microbial populations may be 10- to 100-fold higher than in soil without growing plants (Bottomley, 1998). High populations of microorganisms in the rhizosphere lead to larger numbers of nematodes and protozoa that feed on bacteria and fungi, and in turn, higher populations of microarthropods that prey on nematodes and protozoa.

A soil food web's composition and complexity varies with management (Moore, 1994). The root-microorganism and root-macrofaunal interactions after minimum tillage are vastly different from that after moldboard plowing (Table 2). In no-till cropping systems, microbial activities differ immensely with depth, with the greatest microbial activity

FIGURE 3. The soil food web. Adapted from Hunt et al., 1987.



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occurring near the surface, whereas in the tilled system activities are more evenly distributed throughout the tillage layer (Doran, 1980). The type and functional characteristics of the species present in agroecosystems may be as important as the number of species (Grime, 1997; Hopper and Vitousek, 1997). Bacteria dominate a tillage-based system, whereas fungi and earthworms play a major role in no-till systems (Verhoef and Brussaard, 1990). Microbial community analyses are useful in distinguishing among specific organism populations associated with conventional, minimum and no-tillage cropping systems (Drijber et al., 2000). Invertebrates influence each level of the soil food web, and play a key role in soil OM retention and turnover (Wolters, 2000). Residue quality affects the populations of micro- and mesofauna that colonize residue (vanVliet et al., 2000), and thus rate of residue decomposition and N release. The above ground, herbivorous members of a food web, for example grasshoppers, may alter nutrient cycling within an ecosystem by changing plant abundance and the rate of residue decomposition (Belovsky and Slade, 2000). Soil food dynamics will vary with degree of disturbance and fluctuate with changes in management.

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TABLE 2. Biological attributes of changing tillage systems in select studies.

SOIL ATTRIBUTE[§]	***LENGTH OF STUDY/ YEARS OF SAMPLING***	***SYSTEMS COMPARED******	***RESULTS***	***LOCATION***	***REFERENCE***
Microbial biomass	8 yr/1 yr	MP (20-25 cm) and cultivation to 12 cm	Shallow tillage ↑ microbial biomass.	Sweden	Stenberg, Stenberg and Rydberg, 2000
Microbial biomass, fungal hyphal length	22 yr (mollisol soil) and 39 yr (spodosol soil)/3 yr	NT and CT	NT ↑ microbial biomass, greater contribution of C_{mic} to C_{org}, and greater fungal hyphal length.	Russia	Ananyeva et al., 1999
Microbial biomass, community structure	25 yr/1 yr	NT, sub-till, MP wheat fallow and native sod	Cropping ↑ microbial biomass, no tillage differences in surface 0-15 cm, in fallow NT ↑ microbial biomass. NT ↑ FAME biomarker for AM fungi, PL- and EL-FAMEs differed among tillage treatment in wheat-fallow.	Nebraska	Drijber et al., 2000
Total and active microbial biomass, mineralized C	1 yr/1 yr	NT and CT	NT ↑ active microbial biomass and mineralized C in the top 5 cm, CT and NT = for total microbial biomass.	Argentina	Alvarez and Alvarez, 2000
Microbial biomass C	9 yr/5 yr	Continuous wheat, wheat-pasture, wheat-beans, wheat-fallow with residues burned, incorporated or retained	↑ microbial biomass C when wheat-pasture for first 3 yr and when residues retained or incorporated.	Australia	Ladd et al., 1994
Biomass C, phosphatase, dehydrogenase, microbial diversity	100+ yr/1 yr	Undisturbed prairie, CT wheat-barley-pea rotation	Higher biomass C, phosphatase and dehydrogenase in prairie soil, ↑ microbial diversity in cultivated soil	Washington	Kennedy and Smith, 1995
Soil enzymes	7 to 13 yr/2 yr	NT and CT, varying crop rotations at two sites	Site 1: Higher concentrations of all enzymes with NT and previous history of alfalfa; Site 2: No consistent response of enzymes to tillage practice.	Ontario	Bergstrom, Monreal and King, 1998
Glomalin, arbuscular mycorrhizal fungi	1 to 4 yr/1 yr.	NT and plow tillage	NT ↑ glomalin, leading to greater AS.	Maryland	Wright, Starr and Paltineau, 1999
Fungal communities	10 yr/1 yr	NT and CT, soil and sorghum residue	Residue: CT ↑ density of fungal hyphae, but fewer CFU^{Ψ} than NT Soil: NT ↑ density of fungal hyphae, no differences in CFU^{Ψ}.	Georgia	Beare et al., 1993

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TABLE 2 (continued)

SOIL ATTRIBUTE [§]	***LENGTH OF STUDY/ YEARS OF SAMPLING***	***SYSTEMS COMPARED****	***RESULTS***	***LOCATION***	***REFERENCE***
Fungal biomass, residue decomposition, N immobilization	2yr/2 yr	CT with surface residue and incorporated residue	Surface residue ↑ fungal biomass, ↑ immobilization, ↓ residue decomposition.	Colorado	Holland and Coleman, 1987
Glucosamine:muramic acid, fungal biomass, POM C,TOC, water stable aggregates	12 (ND), 11 (CO), 15 (TX), 26 (NE), 22 (KS), and 26 (KY) yr/1 yr	CT and NT, except CT and tall grass prairie in KS, and CT and bluegrass sod in KY	All values higher for NT.	North Dakota, Nebraska, Colorado, Texas, Kansas, Kentucky	Guggenberger et al., 1999
Soil-borne fungal pathogens of beans	Review article		Tillage ↓ several root diseases.		Abawi and Widmer, 2000
Actinomycetes, algae, bacteria, fungi, nitrifiers	3 yr/3 yr	Burning, NT, CT with soybean-wheat	Bacteria and nitrifiers no change; NT ↑ actinomycetes, algae and fungi early in growing season.	Georgia	Harris et al., 1995
Bradyrhizobia populations and diversity	17 yr/1 yr	NT and CT soybean, wheat-maize, soybean-wheat, maize rotations	NT and soybean rotations > CT and cont. cropping.	Brazil	Ferreira et al., 2000
Microbial diversity	3 yr/2 yr	NT and CT, continuous wheat, red clover-wheat, pea-wheat, fallow-wheat rotations	↑ diversity under NT, and red clover-wheat and pea-wheat rotations than with continuous wheat or fallow-wheat.	Alberta	Lupwayi, Rice and Clayton, 1998
CO_2 flux	13 yr/2 yr	NT and CT continuous wheat and wheat-fallow	Continuous wheat: NT < CT. Wheat-fallow: NT < CT in wheat.	Saskatchewan	Curtin et al., 2000
Collembola, Acarina	11 yr/2 yr	NT, chisel plow, ridge till corn	NT > CT, populations in CT recovered with time.	Ontario, Canada	Neave and Fox, 1998
Mites	1 yr/1 yr	MP, chisel plowing and light cultivation	Tillage ↓ populations.	Germany	Hülsmann and Wolters, 1998
Orbatid mites	Review article	NT and CT	NT > CT		Behan-Pelletier, 1999

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Arthropods	1 yr /10 months	NT and CT wheat	Predators, biomass > in NT; phytophagous CT = NT.	Argentina	Marasas, Sarandon and Cicchino 2001
Arthropods	3 yr/1 yr	NT and CT sorghum with winter clover or winter rye cover crops	Biomass was affected more by type of N source than tillage. Winter rye > winter clover.	Georgia	Blumberg, Hendrix and Crossley, 1997
Ant diversity	Established fields/ 2 weeks	Reduced tillage and CT	Reduced tillage > CT.	North Carolina	Peck, McQuaid and Campbell, 1998
Invertebrates (herbivores, detritovores and predators)	5 yr/5 yr	NT, reduced tillage, CT grain production	NT ↑ detritovores and predators, no differences in herbivores.	NE Australia	Robertson, Kettle, Simpson 1994
Earthworms	5 yr/1 yr	NT and CT, corn-soybean rotation	NT > CT 57% of sites; NT = CT 29% of sites; CT > NT 14% of sites.	Indiana and Illinois	Kladivko, Akhouri and Weesies, 1997
Earthworms	1 yr/1 yr	Alfalfa, NT corn, CT corn	Alfalfa = NT corn > CT corn.	Wisconsin	Gallagher and Wollenhaupt, 1997
Earthworms	5 yr/5 yr	Low/normal tractor traffic	↑ earthworms with low tractor traffic.	Norway	Hansen and Engelstad, 1999
Earthworms	NT 3 yr, chisel disk 3 wk/1 yr	Chisel disk and NT, corn-soybean, cont. corn, cont. soybean rotations	NT > chisel-disk, no difference with rotation or N fertilizer.	Missouri	Jordan et al., 1997
Earthworms	1 yr/1 yr	CT/NT, soybean-corn and wheat-corn rotations	NT soybean-corn > NT wheat-corn > CT	Missouri	Hubbard, Jordan and Stecker, 1999
Earthworms	24 yr/2 yr	NT and CT wheat-fallow	NT > CT	Alberta	Clapperton et al., 1997

§ FAME = fatty acid methyl esters; POM = particulate organic matter; TOC = total organic carbon
* NT = no-till, CT = conventional tillage, MP = moldboard plow
Ψ CFU = colony-forming units

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Microorganisms

The presence of a large and diverse soil microbial community is crucial to the productivity of any agroecosystem, regardless of management. The composition of the microbial community influences the rate of residue decomposition and nutrient cycling in both no-till and tillage-based systems (Beare et al., 1993).

One of the primary roles of fungi is decomposition of plant residues, especially lignin, which is more resistant to decomposition than other plant residue components. This is especially important in a successful no-till system that requires specialized fungi to degrade surface residue, such as cellulose (*Chaetomium*, *Fusarium*, *Trichoderma*) and lignin (Basidiomycetes) decomposers. No-till systems provide for a more diverse population of residue decomposers, and a slower release of nutrients (Curtin et al., 2000; Hussain, Olson, and Ebelhar, 1999). Soil fungi may be responsible for the net N immobilization that often occurs in the surface residue of no-till fields (Frey et al., 2000). Fungal hyphae contribute to higher soil OM content and aggregate stability in surface soils under no-till, and reduce the potential for soil erosion (Guggenberger et al., 1999).

Specialized fungi that form symbiotic relationships with plant roots are mycorrhizae. Mycorrhizal fungi are responsible for translocation of nutrients, especially soil P, and are known to help alleviate water stress during drought conditions (Morton, 1998). Glomalin, a glycoprotein produced by arbuscular mycorrhizae, is well correlated with increased aggregate stability. As the transition period with no-till lengthens, so does aggregate stability and glomalin production (Wright, Starr, and Paltineanu, 1999). Moldboard plowing in a wheat-fallow crop rotation in Nebraska has been shown to markedly reduce the fatty acid methyl ester (FAME) biomarker for mycorrhizal fungi compared to that from no-till (Drijber et al., 2000).

Tillage may negatively affect fungi to a greater extent than other microorganisms, such as bacteria, because of the physical severing of the hyphal mat or hyphal strands that can form after long periods with little disturbance. Because of the physical disruption of fungal hyphae with cultivation, movement of fungi through cultivated soils is reduced. In no-till systems a higher proportion of fungal decomposers are found, while cultivated systems favor higher populations of bacterial decomposers (Hendrix et al., 1990). At six sites (North Dakota, Nebraska, Colorado, Texas, Kansas and Kentucky) of a study comparing no-till and conventional tillage, fungal biomass was greater than bacterial biomass in the no-till fields (Guggenberger et al., 1999). Fungi are responsible for causing many soil-borne plant diseases (Cook and Haglund, 1991). Diseases such as Rhizoctonia may be more devastating in no-till systems where there is no severing of hyphal strands (Weller et al., 1986).

Bacteria are also decomposers in soil, especially in tillage-based systems (Beare et al., 1993), and are crucial for mineralization of nutrients, making them available to plants and other organisms. Soil bacteria also aid in weathering soil minerals, contribute to soil formation, and secrete polysaccharides to hold soil particles together and promote aggregate stability. Some bacteria produce antibiotics that affect other organisms. Root-colonizing bacteria affect plant growth by producing root growth-promoting hormones, and some have the potential for use as biological control agents (Alexander, 1998). Actinomycetes are a specialized group of soil bacteria. They are able to degrade plant materials such as cellulose, mineralize nutrients, and some produce antibiotics. Actinomycetes may tolerate low soil water potential better than other bacteria, but they are not tolerant of low soil pH (Alexander, 1998). Early in the growing season, undisturbed fields in Georgia with soybean surface residue had the highest numbers of actinomycetes and fungi compared to burned or tilled treatments (Harris et al., 1995).

The dynamics of bacterial functions in soil can change with tillage. In a study of the diversity of prairie and cultivated soils in Washington, microbial diversity indices were greater in cultivated systems compared to undisturbed grassland (Kennedy and Smith, 1995). With tillage, greater residue surface area was in contact with the soil and more substrate was available for colonization and more microbial activity occurred. The increase in microbial diversity with disturbance indicates a change in the microbial community to one that exhibits a greater range of substrate utilization and resistance to the stress of cultivation. In contrast to the Kennedy and Smith (1995) results, Lupwayi, Rice, and Clayton (1998) showed that crop rotation and reduced tillage support greater microbial diversity than conventional tillage as shown by a reduction in substrate richness and evenness. Their study promoted no-till as a component of sustainable agriculture systems. This is one example of the many contradictory results that may be due to differences in soils, climates and vegetation as well as degree of soil disturbance.

Algae are photoautotrophic organisms that are found in soil at populations of 10^3-10^4 per gram of soil, far fewer than bacteria and fungi. Numbers of algae are positively related to soil moisture and light (Shimmel and Darley, 1985), and negatively related to soil depth. Algae assist in N fixation and soil aggregate stability. They are susceptible to

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soil disturbance and may be good indicators of soil quality. Algae are positively affected by reduced tillage and maintaining surface residue which allows for a higher moisture regime for longer periods of time, and fosters algal growth on the soil surface (Harris et al., 1995).

Micro- and Mesofauna

In any soil community the presence of the various trophic groups is critical to the functioning of that soil. The intermediate-size group of micro- and mesofauna function as both predators of microorganisms and a food source for macrofauna. Protozoa, nematodes, and mites are important members of the soil food web because of their contributions to residue decomposition and nutrient cycling. Protozoa are considered to be microfauna because of their size (< 200 μm long), while nematodes and mites are categorized as mesofauna (200-1000 μm long).

Protozoa are crucial to the functioning of the soil food web and other ecosystems because of their roles as consumers of bacteria (Wood, 1989) and for nutrient cycling and aiding in providing energy for microorganisms, plants, and animals (Foissner, 1999). The fluctuations in microbial populations with tillage will also affect protozoan populations since protozoa feed on these organisms. Protozoa may be useful indicators of changes in soil quality because they react rapidly to changes in the environment; however, there is a need for improved methodology to accurately count and identifying protozoa and other soil organisms (Foissner, 1999).

Nematodes are multicellular, round worms that may occur in numbers as large as several million meter^{-2} of surface soil (Ingham, 1998). They can be sub-divided into groups based on their functional roles: bacterial feeding, fungal feeding, root feeding, predatory, and omnivorous. They are key in the turnover of microbial communities through predation and nutrient release. Nematodes and protozoa may graze discriminately upon bacteria and fungi, thus altering the microbial community in soil, and altering residue decomposition rates (Ingham, 1998). Some are plant parasites; however, most rely on other organisms as a food source (Wood, 1989). Tillage negatively affects populations of larger nematodes (Jones, Larbey, and Parrott, 1969; Oostenbrink, 1964).

Mites (Acari) are very sensitive to the presence of litter or residue. Mechanical disturbance of surface residue has a negative effect on mite populations and species diversity. No-till cropping had a positive effect on abundance and richness of Collembola and Acarina, with the residue regulating extremes of high temperature and loss of moisture compared

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to tillage (Neave and Fox, 1998). Hulsmann and Wolters (1998) also found the greatest negative effects of tillage on soil mites soon after tillage had occurred. While no-till may enhance the residue levels in surface soils, thus enhancing mite populations, use of the herbicide Atrazine in a no-till situation had a negative effect on mite populations (Moore et al., 1984).

Macrofauna

Arthropods such as millipedes (Diplopoda) and centipedes (Chilopoda) play a critical role in soil quality maintenance. Arthropods are important in OM formation, soil structure and soil pore formation due to their mechanical activity (Zunino, 1991). Tillage systems affect arthropod fauna by altering the proportion of functional arthropod groups found in soil (Marasas, Sarandon, and Cicchino, 2001), with the abundance and diversity of animal species decreasing with increasing tillage intensity (Alderweireldt, Konjev, and Polett, 1991; Pfiffner and Niggli, 1996). There is an increase in biodiversity of edaphic taxa of arthropods under no-till, with predators comprising the highest numbers (Robertson, Kettle, and Simpson, 1994; Stinner and House, 1990). Moldboard plowing decreases predator numbers, while no-till favors more predatory activity due to reduced mechanical disturbance and greater residue cover.

Tillage impacts the numbers of arthropods, with greater numbers found under no-till than under minimum or conventional tillage (Marasas, Sarandon, and Cicchino, 2001; Roberston, Kettle, and Simpson, 1994). In both of those studies, functional groups (predators, detritovores, phytophagous) were affected to different degrees as tillage level was reduced. Cropping system differences may confound clear conclusions about the effect of tillage on arthropods. In some cases, arthropod populations may respond more to cropping practices than to tillage. In a 7-year study in New Zealand, intensive tillage did not adversely affect arthropod populations compared to hand-hoeing, but that effect was most likely due to higher quality litter present with high weed infestations prior to cultivation (Wardle et al., 1999). Presence of greater weed biomass was more favorable to arthropods than either a perennial crop [asparagus (*Asparagus officinalis* L.)] or an annual crop [corn (*Zea mays* L.)]. Tillage treatment (no-till or conventional) played a smaller role in determining arthropod biomass than did type of cover crop, with arthropod numbers and biomass greater on sorghum (*Sorghum bicolor* L.) that followed a winter rye (*Secale cereale* L.) cover crop in Georgia, compared to a winter clover cover crop (Blumberg, Hendrix, and

Crossley, 1997). Neave and Fox (1988) found that cryptozoic invertebrates became more abundant under no-till especially in summer, but their numbers in conventional tillage, chisel or ridge tillage treatments increased later in the season.

Ants (Hymenoptera: Formicidae) may be useful as bioindicators of the effects of management practices in agroecosystems (Peck, McQuaid, and Campbell, 1998). In North Carolina where minimum and conventional tillage were compared, most species of ants preferred the undisturbed field margin to the cultivated areas. Of the ant species inhabiting cropland, 76% were found in fields prepared with minimum tillage (Peck, McQuaid, and Campbell, 1998).

Earthworms may be early and visual indicators of reduced tillage in some soils. No-till systems have the potential to increase populations of earthworms in agricultural fields (Clapperton et al., 1997; Jordan et al., 1997). The populations of shallow-dwelling earthworms (*Apporectodea tuberculata* and *A. trapezoides*) were greater in no till soils at 8 of 14 sites in Indiana and Illinois when compared with paired conventional tillage soils (Kladivko, Akhouri, and Weesies, 1997). Greater quantity of residue, and lower C:N ratio of residue in a no-till corn-soybean rotation in Missouri led to higher populations of earthworms (*A. trapezoides*) than a no-till wheat-corn rotation, and both of these treatments had more earthworms than the conventionally tilled treatments (Hubbard, Jordan, and Stecker, 1999). Cropping systems in Norway that reduced compaction through low tractor traffic compared to normal tractor traffic had higher populations of earthworms; however, species composition did not change regardless of traffic (Hansen and Engelstad, 1999). Earthworm populations are higher in soils after chisel-type implements that slice the soil without the mixing and inversion of soil by disc plows (Paoletti, Schweigel, and Favretto, 1995).

High populations (40-60 earthworms m^{-2}) of earthworms (*Lubricus terrestris* L.) impact residue management strategies for no-till fields in Wisconsin due to their ability to bury large quantities of surface residue (122 g biomass m^{-2} from October to May) which may expose the soil surface to the potential of rain drop and splash erosion (Gallagher and Wollenhaupt, 1997). Earthworm middens at the soil surface of a no-till field in Ohio were found to enhance soil quality and productivity because they contain greater soil water, coarse organic litter (>2 mm), total C and N, C:N ratio, microbial activity, NH_4-N, and dissolved organic N than bulk soil from outside the cornfield (Subler and Kirsch, 1998). These middens contribute to the spatial heterogeneity in soils. While earthworms burial of residue may impact residue management, many of

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the positive attributes associated with earthworm activity affect agro-ecosystem processes of water infiltration (Edwards et al., 1992), residue decomposition (Subler and Kirsch, 1998), and N-cycling (Parkin and Berry, 1999).

METHODS FOR MEASURING CHANGES IN SOIL ECOSYSTEMS WITH TILLAGE

Many methods are currently used by researchers to help quantify biological diversity and to compare the effects of management practices on the soil ecosystem. Along with plate counts and emergence traps, other methods are now available, enhancing our ability to measure changes in the soil biota. Microbial plate counts do not provide accurate community structure information of soils due to the issue of culturability; however, they still provide a measure of a portion of the population (Dodds et al., 1996; Kennedy and Smith, 1995). Substrate utilization patterns have been used to study community structure and indicate functional diversity and metabolic potential (Bossio and Scow, 1995; Degens, 1999; Garland, 1996; Haack et al., 1995; Zak et al., 1994). To qualitatively characterize soil microbial communities, whole soil fatty acid methyl ester (FAME) analysis is used in microbial community investigations (Cavigelli, Robertson, and Klug, 1995; Kennedy and Busacca, 1995; Zelles et al., 1994).

Molecular genetic techniques are the most recent tool for characterizing soil microbial communities. Nucleic acid analyses have shown that several thousand independent genomes can be present in 1 g of soil (Torsvik, Goksoyr, and Daae, 1990). Methods such as denaturing gradient gel electrophoresis (DGGE) (Muyzer and Uitterlinden, 1993) and single strand conformation polymorphism (SSCP) (Lee, Zo, and Kim, 1996) allow comparisons of microbial similarities among whole soil community samples. DNA reassociation (diversity), percent G+C composition of community DNA (species composition), and DNA:DNA hybridization (similarity and relative diversity) (Griffiths, Ritz, and Glover, 1996) can also be used in community analyses. DNA microarray technology has been used to rapidly analyze microbial communities based on phylogenetic groupings (Guschin et al., 1997).

There are several methods of analysis for larger soil biota including those for nematodes (Yeates and Bongers, 1999), protozoa (Foissner, 1999), and mites (Behan-Pelletier, 1999; Koehler, 1999). Traps of various designs are used routinely for collection of soil fauna that are soil

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quality indicators (Coleman et al., 1999; Paoletti, 1999). These methods require an inventory of the material collected with standard methods of collection and taxonomic identification. Protozoa are enumerated by two methods, either direct counts or by a culture technique (Coleman and Crossley, 1996). In the culture technique, population density is determined by the activity after a bacterial inoculum is added to soil suspensions as a food source for protozoa. Several procedures are acceptable for extracting nematodes from soil, including the Baermann funnel method, filtration, decanting and sieving, elutriation, or flotation/centrifugation (Coleman and Crossley, 1996; Nieminen and Setala, 1998; Yeates and Bongers, 1999). Soil collembolans and mites can be extracted from soil cores or litterbags using a Tullgren apparatus (Nieminen and Setala, 1998), Berlese funnel (Coleman and Crossley, 1996), or some modification of the two (Behan-Pelletier, 1999). Mites may be extracted from soil using funnel extraction with warming, or by mechanical extraction with heptane flotation (Koehler, 1999).

Cryptozoic fauna may be sampled by randomly placing cryptozoa boards (Neave and Fox, 1998) on the soil surface. Peck et al. (1998) used pitfall traps partially filled with glycerin, ethanol and water to collect ants for counts and identification. Earthworms can be extracted from soil following a surface application of dilute formalin solution (Subler and Kirsch, 1998), but the most widely used method involves hand sorting from soil cores (Gallagher and Wollenhaupt, 1997; Hansen and Engelstad, 1999; Hubbard, Jordan, and Stecker, 1999; Paoletti, 1999).

The methods that can be used in ecological studies are as varied as the organisms found in the soil, yet these ecological investigations are still hindered by the available techniques. As the technology advances in the area of molecular ecological investigations, so too will advance our understanding of the dynamics and complexity of soil ecology.

CONCLUSION

With sustainable agricultural practices becoming a priority for growers and the general public alike, an in-depth understanding of the soil ecosystem is needed. Studies of agroecosystem changes during the transition to no-till are needed to minimize the impact of agriculture on the environment. The soil biota, its interactions and distribution are critical to the functioning of any agricultural system. Long-term cultivation has a profound effect on biotic populations, processes and community structure. There are varying levels of disturbance between conventional tillage and no-till, and each level exerts a different effect on the soil environment. The "transition period" of no-till is characterized by soil physical, chemical and biological changes that may affect in soil productivity. In order to better manage this time of transition, growers may increase cropping intensity, experiment with different crop rotations, and introduce new crop species–all of which may further alter the soil environment and lead to changes in the soil biota. Thorough examination of soil environmental changes during the transition period is warranted so that growers may successfully reduce tillage, while reducing economic risk.

Almost all groups of soil organisms are negatively impacted by soil disturbance. Only a small portion of the microbial or faunal groups can currently be collected and studied, which provides only a partial picture of soil communities. However, several new methods are available that will enhance our knowledge of what is occurring in soil. What is presently known about the living soil is minuscule, but as laboratory techniques become more sophisticated and more research is conducted, we will gain a better understanding. The degree of soil disturbance, and the quantity, type and quality of residue in a cropping system all add to the complexity of the system and result in varying results and conclusions found in the literature. Population and process level studies, as well as investigations at the ecosystem and functional level, are needed to develop management systems that include soil biota for successful sustainable cropping systems. Ecological investigations will enhance the understanding of changes that occur with the adoption of minimum tillage and no-till cropping systems so that these systems become increasingly viable.

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